

Stellar Encounters with the Oort Cloud Based on Hipparcos Data.

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ABSTRACT

We have combined Hipparcos proper motion and parallax data for nearby stars with ground-based radial velocity measurements to find stars which may have passed (or will pass) close enough to the Sun to perturb the Oort cloud. Close stellar encounters could deflect large numbers of comets into the inner solar system, which would increase the impact hazard at the Earth. We find that the rate of close approaches by star systems (single or multiple stars) within a distance D (in parsecs) from the Sun is given by $N = 4.2 D^{2.02} \text{ Myr}^{-1}$, less than the numbers predicted by simple stellar dynamics models. However, we consider this a lower limit because of observational incompleteness in the Hipparcos data set. One star, Gliese 710, is estimated to have a closest approach of less than 0.4 parsec, and several stars come within about 1 parsec during about a ± 10 Myr interval. We have performed dynamical simulations which show that none of the passing stars will perturb the Oort cloud sufficiently to create a substantial increase in the long-period comet flux at the Earth's orbit. We have begun a program to obtain radial velocities for stars in our sample with no previously published values.

Subject headings: comets:general — solar system:general — stars:kinematics — solar neighborhood

1. INTRODUCTION

The solar system is surrounded by a vast cloud of about 10^{12} – 10^{13} comets with orbits extending to interstellar distances, called the Oort cloud, and with a total estimated mass of some tens of Earth masses (Oort 1950, for a recent review see Weissman 1996a). The boundary of stable cometary orbits, that is the outer dimensions of the Oort cloud, is a prolate spheroid with the long axis oriented toward the galactic nucleus, and with maximum semi-major axes of about 10^5 AU for direct orbits of comets oriented along the galactic radius vector, about 8×10^4 AU for orbits perpendicular to the radius vector, and about 1.2×10^5 AU for retrograde orbits (those opposite to the direction of galactic rotation) (Smoluchowski & Torbett 1984, Antonov & Latyshev 1972). These cometary orbits are perturbed by random passing stars, by giant molecular clouds and by the galactic gravitational field. In particular, close or penetrating passages of stars through the Oort cloud can deflect large numbers of comets into the inner planetary region (Hills 1981), initiating Earth-crossing cometary showers and possible collisions with the Earth. Sufficiently large impacts or multiple impacts closely spaced in time could cause biological extinction events. Some terrestrial impact craters and stratigraphic records of impact and extinction events suggest that such showers may have occurred in the past. Dynamical models (e.g., Hut et al. 1987, Fernandez & Ip 1987) show that a cometary shower has a typical duration of about 2–3 million years.

Evidence of the dynamical influence of close stellar passages on the Oort cloud could come from the distribution of cometary aphelion directions. Although the distribution of long-period (10^6 to 10^7 years) comet aphelia is largely isotropic on the sky, some non-random clusters of orbits exist and it has been suggested that these groupings record the tracks of recent stellar passages close to the solar system (Biermann et al. 1983). However, Weissman (1993) showed that it would be difficult to detect a cometary shower

in the orbital element distributions of the comets, except for the inverse semi-major axis ($1/a_o$) energy distribution, and that there is currently no evidence of a cometary shower in this distribution.

Some work has been done in the past to search for stellar perturbers of the cometary cloud. Mülläri & Orlov (1996) used ground-based telescopic data to predict close encounters with the Sun by stars contained in the Preliminary Version of the Third Catalogue of Nearby Stars (Gliese & Jahreiss 1991). They found that three stars may have had, and 22 may have encounters with the Sun within 2 parsecs, with predictions being valid over about ± 1 million years from the present epoch. Matthews (1994) made a similar study, which was limited to stars in the solar neighborhood within a radius of about 5 pc, and he listed close approach distances for six stars in the near future, within 5×10^4 years.

However, the accuracy of most ground-based parallax and proper motion measurements is limited to several milliarcseconds or milliarcseconds per year, respectively. This measurement accuracy imposes a severe limitation on the accuracy of predictions on past or future close stellar passages.

Using data from the Hipparcos satellite, we have searched for nearby stars which have passed or will pass close to the Sun, in order to identify those passages which could cause a significant perturbation on the orbits of comets in the Oort cloud. We have selected a sample of stars and also measured radial velocities for a fraction of these stars, most of them with no previous measurements. The Hipparcos mission provided very accurate parallax and proper motion measurements with a median precision of less than 1 milliarcsecond and 1 milliarcsecond per year, respectively. The basic astrometric data in the Hipparcos Catalogue (ESA 1997) include positions, trigonometric parallaxes, proper motions, their standard errors and correlation coefficients for about 120,000 stars. The Hipparcos proper motions are quasi-inertial to within ± 0.25 milliarcsecond per year, as the link between

the Hipparcos Reference Frame and the ICRS (International Celestial Reference System) implies.

In this paper we study which stars in our sample could have a close passage by assuming a simple linear motion model and we also estimate the frequency of stellar encounters with the solar system. Close stellar passages mainly perturb comets near their aphelions, causing changes in the perihelion distance and inclination of the orbits of long-period comets. For those passages which most likely could affect the cometary orbits, we have modeled the perturbations through dynamical simulations. In future papers we will report the individual radial velocities we have measured, with a discussion of the orbital solutions for non-single stars, and we will study the stellar passages using a larger sample, including integration of their orbits in the galactic potential.

2. OBSERVATIONAL DATA AND ANALYSIS

Significant perturbations of the Oort cloud are possible out to a distance of about 2–3 pc. We selected 1,208 stars from the Hipparcos Catalogue (ESA 1997), whose proper motion combined with an assumed maximum radial velocity of 100 km s^{-1} implied an impact parameter of 3 parsecs or less. This radial velocity is two to three times the local stellar velocity dispersion, to allow intrinsically higher velocity stars to be included. At that velocity, this requirement meant that stars whose proper motion in milliarcseconds per year was less than 0.06 times the square of the parallax in milliarcseconds, for parallax values greater than 4.5 milliarcseconds, are the best candidates to have approaches within 3 pc from the Sun over about ± 10 Myr from the present epoch. For smaller parallax values the implied proper motion limit is close to or below the Hipparcos measurement accuracy.

In order to predict past or future close stellar encounters with the Sun, we searched for published radial velocity measurements in the literature and also made new observations of

several stars. We found values for 573 of our 1,208 stars (about 47% of the sample), which were combined with the Hipparcos Catalogue data to calculate the time and distance of the close passages assuming straight-line motion.

We have investigated several effects which might make a simple rectilinear motion model inadequate, including multiple scattering by other stars along a star’s path toward or away from the Sun and differential acceleration between the Sun and the star due to the large scale galactic potential. The effect of stellar interactions is small: a star passing 1 parsec from a one solar mass star with a relative velocity of 20 km s^{-1} results in an angular deflection of only 4.5 arc seconds. Even over a path length of 100 parsecs, the r.m.s. deflection due to such encounters (assuming a local stellar density of 0.1 pc^{-3}) is less than 1 arc minute. This deflection at 100 parsecs would change the impact parameter by less than 0.03 parsec. We also estimated the differential acceleration of the Sun and the nearby star in the galactic potential. Assuming an axially symmetric and stationary galactic potential field, the force laws parallel and perpendicular to the galactic plane can be used to estimate this differential acceleration in the solar neighborhood. Assuming IAU galactic parameters (Kerr & Lynden-Bell 1986), the change in the Sun-star encounter distance induced by the potential field from that given by a rectilinear motion, at a time equal to the time of closest approach T , is

$$\delta_R \simeq 1.4 \times 10^{-4} \text{ pc} \left(\frac{T}{\text{Myr}} \right)^2 \left(\frac{2d_R + d_{Rc}}{\text{pc}} \right) \quad (1)$$

and

$$\delta_Z \simeq 7.1 \times 10^{-4} \text{ pc} \left(\frac{T}{\text{Myr}} \right)^2 \left(\frac{2d_Z + d_{Zc}}{\text{pc}} \right) \quad (2)$$

in the galactic plane and perpendicular directions, respectively, where d_R is the difference between the current galactocentric distance of the Sun and that of the star in the galactic

midplane, d_{Rc} is the difference at time T , d_z is the difference between the current vertical distance of the Sun and the star from the midplane, and d_{zc} the difference at time T . An upper limit to the change in encounter distance for time T is given by $\delta_{\text{total}} = \sqrt{\delta_R^2 + \delta_z^2}$. This change can be neglected for most of our sample stars, although for a few stars could be important, as we will point out later.

2.1. Radial velocities

In most cases the uncertainty in the closest approach distance is dominated either by uncertainties in the published radial velocity measurements or by uncertainties in the barycentric motion of binary systems. For the stars in our sample that are part of multiple star systems, orbital motion could contribute to the measured values of both proper motion and radial velocity, and our estimates of the uncertainty in miss distances may have to be increased. For some of these binary or multiple systems the systemic radial velocity is reported in the literature, whereas for some other systems it is not clear whether it is the systemic radial velocity or the radial velocity of one component that is reported. Other stars show long-term changes in their radial velocities which could imply that they belong to long-period binary or multiple systems with unidentified companions.

Also, for a few stars the radial velocity uncertainty is not reported in the literature, or the authors only report the probable error for the combined list of observed stars in which the one of interest is included. In these cases it is difficult to derive an accurate error estimate for the calculated closest approach distance and time.

We also measured new radial velocities for some of the stars, mostly those with no previously published values. For these observations we used the Center for Astrophysics (CfA) Digital Speedometers (Latham 1985, 1992), primarily on the 1.5-m Wyeth Reflector at the Oak Ridge Observatory in Harvard, Massachusetts, but also on the 1.5-m Tillinghast

Reflector and the Multiple Mirror Telescope at the F. L. Whipple Observatory atop Mt. Hopkins, Arizona. With the CfA Digital Speedometers, single-order echelle spectra centered near 5187 \AA are obtained with photon-counting intensified Reticon detectors at a spectral resolution of 8.3 km s^{-1} over a 45 \AA window.

The radial velocities were derived using cross-correlation techniques following the general approach outlined in Nordström et al. (1994). The templates were drawn from an extensive grid of synthetic spectra calculated by Jon Morse using Kurucz (1992a,b) model atmospheres. For the template parameters we adopted solar metallicity and surface gravity $\log g = 4.5$ throughout, and ran extensive grids of correlations in effective temperature and rotational velocity in order to determine the template which gave the highest peak correlation value averaged over all the exposures. These techniques yield a precision of about 0.5 km s^{-1} for a single velocity measurement of a slowly-rotating solar-type star, with an absolute accuracy of about 0.1 km s^{-1} in the zero point of the CfA velocity system. The precision of a single velocity measurement degrades with increasing rotational velocity, and can be as poor as 2 or 3 km s^{-1} near the limiting value of $v \sin i$, about 140 km s^{-1} , that can be handled by the CfA procedures. For the coolest M dwarfs and for stars with very rapid rotation, the absolute zero point of the CfA velocity system may be uncertain by as much as 1 km s^{-1} because of template mismatch.

The results of the CfA velocity measurements for the stars included in this paper are summarized in Table 1. Column 1 lists the Hipparcos identification; the next two columns give the effective temperature, T_{eff} , and rotational velocity, $v \sin i$, adopted for the template; and columns 4 and 5 report the number of observations and time span between the first and last observations. The average velocity in column 6 is followed by several error estimators: the standard deviation of the average velocity; then in column 8 the external r.m.s deviation of the individual velocities from the mean; then in column 9 the average of the internal velocity error estimates from our cross-correlation package, XCSAO (Kurtz et

al. 1992) running under the IRAF² environment; then in column 10 the ratio of the external to internal errors; then in columns 11 and 12 the observed χ^2 and $P(\chi^2)$, the probability that a constant star might show, by accident, a χ^2 value larger than we actually observe. The final column gives the name assigned by the CfA observing catalogs if the star was originally observed for another project, and in a few cases a code for suspected single-lined binaries, S?, and definite velocity variables, S.

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It is important to identify spectroscopic binaries among our targets, because orbital motion can introduce a significant deviation of a single velocity measurement from the center-of-mass velocity for the system, especially for short-period binaries where the orbital amplitude can be tens of km s^{-1} . In the past it has been traditional in the radial-velocity community to use the ratio of the external to internal errors, e/i , as an indicator of intrinsic velocity variation. For example, stars with $e/i > 2$ were often identified as possible binaries. The e/i test is not well suited for stars with only a few observations, because the external error estimate is vulnerable to statistical fluctuations. For stars with just a few observations we prefer to use $P(\chi^2)$. For example, stars with $P(\chi^2)$ less than some small value, such as 0.01 or perhaps 0.001, are very unlikely to be intrinsically constant. Two of the stars in Table 1, HIP 21386 and 39986, have large e/i ratios and very small $P(\chi^2)$ values. Plots of the velocity histories for these stars confirm that there are significant variations in their velocities, and there is little doubt that they are binaries. The error indicators for one of the stars, HIP 11559, suggest that it may also be a variable, but the evidence is very marginal.

²IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

$P(\chi^2)$ is a less useful test for stars with many observations. The problem is that $P(\chi^2)$ assumes that the errors are exactly Gaussian, while real data sets always have outliers. Very subtle deficiencies in the internal error estimates can get translated into extreme values of $P(\chi^2)$ for stars with dozens of observations. This problem is illustrated by the results for the M dwarfs with Gliese identifications in Table 1. Those targets have been observed for many years for another project and have much richer data sets than the stars which were new targets for the present project.

The stars in Table 1 include two visual binaries, HIP 75311 with an angular separation of $3.25''$, and HIP 91768 and 91772 (Gliese 725A and 725B) separated by $13.3''$. For each of these systems the velocities of the individual members are quite similar, confirming the conclusion already reported in the Hipparcos data base that they are physical binaries and not accidental alignments on the sky. For these visual binaries one should use the center-of-mass velocity for the system. In both cases the member stars must have nearly the same masses because they have very similar brightnesses, so it should be adequate to calculate the center-of-mass velocity simply by averaging the velocities of the two components. For HIP 75311 this gives a system velocity of $-14.3 \pm 0.3 \text{ km s}^{-1}$, and for Gliese 725 a system velocity of $0.15 \pm 0.1 \text{ km s}^{-1}$. The case of Gliese 725 is especially interesting, because the system velocity is so close to zero, and it is not even clear whether it is approaching or receding from the solar system. In this case a very large error in the predicted time of close approach would result if one used the velocities now observed for the individual components. Indeed, that erroneous procedure would predict that Gliese 725 is approaching the solar system, but 725 B is receding. This is an extreme example of the importance of including the effect of orbital motion in a binary.

3. RESULTS

The stars we found with a closest approach distance within 5 pc of the Sun are listed in Table 2 in order of increasing miss distance. These predicted passages are concentrated in a time interval of about ± 10 Myr, with most occurring within ± 4 Myr. Some passages have a large uncertainty, mainly because of a large error in the measured parallax or proper motion; the miss distance and encounter time reported for these passages should be considered with caution. Some stars in the Table are reported with a miss distance which might need to be revised according to the upper limit error estimate δ_{total} discussed above. In the list of 154 stars reported in the Table, we find six stars (HIP 2365, HIP 15929, HIP 17085, HIP 43175, HIP 57791 and HIP 88847) whose value of δ_{total} is larger than the uncertainty in miss distance reported, and 11 (the six above plus HIP 11559, HIP 39986, HIP 52097, HIP 101573 and HIP 103659) with δ_{total} larger than half the value of the miss distance. We mark these stars in the Table. Stars coming within about 2–3 pc are potential perturbers of the Oort cloud. In particular, one of these, GL 710 (HIP 89825), is the best candidate to have a future penetrating passage through the Oort cloud.

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The closest approach distances versus time of past (negative times) or future (positive times) encounters are shown in Figure 1. The size of the data point for each star is proportional to the visual brightness of the star at the minimum distance. From this plot we see that the passages at large times are dominated by stars with the largest apparent brightness at closest approach. This suggests an observational bias, which can be explained if one notes that most of the stars that had or will have a close passage at large times from the present epoch could only have been observed by Hipparcos if they are intrinsically bright.

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The frequency of stellar passages within any distance, D , of the Sun can be estimated by $N = \pi D^2 v_{\odot} \rho_*$, where v_{\odot} is the velocity of the Sun relative to the stars and ρ_* is the local density of stellar systems. Mignard (1997) found values for the solar motion of 16.1 to 21.2 km s⁻¹ relative to the local standard of rest as measured relative to various stellar types, based on Hipparcos data for stars within 2 kpc of the Sun and within 30° of the galactic plane. Also using Hipparcos data, Mignard found that the velocity dispersions of stars in the solar neighborhood ranged between 17.1 and 42.6 km s⁻¹, again depending on stellar type. We assume a value of 40 km s⁻¹, since most encounters will be with the more numerous, higher velocity solar-type and late-type stars. If we root-sum-square this value with a nominal value of 20 km s⁻¹ for the solar motion, then the mean encounter velocity of stars or star systems with the Sun is on the order of 45 km s⁻¹.

A current best estimate for the local density of stellar systems (single or multiple stars), ρ_* , within 5 pc of the Sun is 0.086 pc⁻³ (Henry 1997). Combining this value with the nominal value of 45 km s⁻¹ found above and assuming an encounter distance of ≤ 1 pc, gives $N = 12.4$ Myr⁻¹. Earlier estimates by Weissman (1980) and Fernandez and Ip (1991) found values for N of 5.1 and 7 Myr⁻¹, respectively, assuming somewhat different input values.

A logarithmic plot of the cumulative number of predicted stellar encounters from our Hipparcos data between the Sun and passing stars within 5 pc is shown in Figure 2. This data is for 88 stellar systems in our sample with measured radial velocities and encounter times within ± 1 Myr. The dashed line in the figure is a least squares fit to the data which has a slope of 2.02 ± 0.03 , in excellent agreement with theory. Assuming similar statistics for the total sample, we find a value of 4.2 stellar systems per Myr passing within 1 pc, considerably less than the value estimated above. The r.m.s. encounter velocity of the stars

in our sample with the solar system is 52 km s^{-1} , in good agreement with the estimate above. Assuming the above stellar system density, this velocity would result in an expected frequency of encounters of $N = 14.3 \text{ Myr}^{-1}$ for an encounter distance $\leq 1 \text{ pc}$. The solution to this apparent disagreement is likely due to observational incompleteness in our sample. The Hipparcos Catalogue is complete to about magnitude 7.3-9.0, depending on galactic latitude and spectral type, and has a limiting magnitude of about 12. Consequently, fainter, low mass stars near the periphery of our search area were likely missed. This observational incompleteness is also evident in the decrease in encounter frequency and the increase in the mean brightness of the stars encountering the solar system as one moves away from the present epoch in time.

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3.1. Past and Future Close Approaches

From Table 2 we see that 154 stars are predicted to come within a distance of 5 pc during a time interval of about $\pm 10 \text{ Myr}$, with roughly similar numbers of close approaches in the past and the future (70 and 84, respectively). For all stars with a closest approach distance of less than 3 pc, the variation with time of the separation distance between each star and the Sun is shown in Figures 3 and 4 for time intervals of 2 Myr in the past and 2 Myr in the future, respectively.

EDITOR: PLACE FIGURE 3 HERE.

EDITOR: PLACE FIGURE 4 HERE.

The star with the closest future passage in the sample is GL 710. The predicted minimum distance for this star is $71 \pm 33 \times 10^3$ AU (0.342 pc) and the encounter time is 1.36 ± 0.04 Myr in the future (see discussion below for the assumptions made in this calculation). Another predicted close passage is by SAO 128711 (HIP 1692), with a miss distance of $57 \pm 1045 \times 10^3$ AU (0.276 pc) and an encounter time 1.24 ± 0.95 Myr in the past. The uncertainties in miss distance and encounter time for SAO 128711 are large, because of the large error in its measured proper motion. Thus, we cannot estimate a reliable miss distance for this star. These two stars are the only ones with predicted miss distances less than 10^5 AU (~ 0.5 pc).

Close stellar passages within 3 pc during a time span of ± 100 kyr from the present are shown in Figure 5. The best determined miss distances for our sample are obtained for this interval of time. The trajectories of the stars are plotted along with the corresponding uncertainties in the distance and time of closest approach. Several stars come within about 1 pc of the Sun.

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Proxima Centauri (HIP 70890) is currently the nearest star to the Sun. Based on its proximity on the plane of the sky and similar distance, Proxima is commonly thought to be a third component of the binary system α Centauri A/B (HIP 71683 and HIP 71681). However, kinematic data do not allow a bound orbit for Proxima to be unambiguously determined. The value of -15.7 ± 3.3 km s⁻¹ for the radial velocity of Proxima (Thackeray 1967) raises some questions about the bound hypothesis (see Matthews & Gilmore 1993 and Anosova et al. 1994 for discussion). On the other hand, a value of -21.7 ± 1.8 km s⁻¹ based on more precise unpublished measurements of the radial velocity of Proxima made during ESO's Coravel program, led Matthews & Gilmore (1993) to suggest that Proxima

is a bound member of the α Centauri system. Matthews (1994) used a radial velocity of -22.37 km s^{-1} for Proxima, required to account for the bound hypothesis with the implied semimajor axis of Proxima's orbit. Matthews found a closest approach distance for Proxima of 0.941 pc, 26.7 kyr from now. For the α Centauri A/B system he found a closest approach distance of 0.957 pc in about 28.0 kyr. Our results of 0.954 pc in 26.7 kyr for Proxima (using the radial velocity value of -21.7 km s^{-1}) and 0.973 pc in 27.8 kyr for the barycenter of α Centauri A/B are consistent with these earlier predictions. Also in good agreement is the close passage of Barnard's star (HIP 87937), which will have its closest approach to the Sun 9.7 kyr from now at a distance of 1.143 pc according to our results.

In the study carried out by Mülläri & Orlov (1996), several close encounters with the Sun are predicted using data from the Preliminary Version of the Third Catalogue of Nearby Stars (Gliese & Jahreiss 1991). For this calculation they consider both straight line motion of the stars with respect to the Sun and also the motion of the stars in the galactic potential model of Kutuzov & Ossipkov (1989). They find a good agreement between the results from both methods. In general, the values of Mülläri & Orlov for the stars contained in our sample are in agreement with our results, though there are some differences as well. In particular, GL 473, which was not observed by Hipparcos because it is too faint (visual magnitude 12.5, Landolt 1992), is predicted to have a future closest approach of $60 \times 10^3 \text{ AU}$ in 7,500 years. However, the radial velocity of -553.7 km s^{-1} listed in the catalogue for this star is likely much too high, so the predicted miss distance should actually be much larger. GL 473, a very low mass binary system (see, e.g., Schultz et al. 1998), is reported to have radial velocities of -5.0 km s^{-1} (Wilson 1953), $+19.0 \text{ km s}^{-1}$ (Reid et al. 1994) and $+6.7 \text{ km s}^{-1}$ (Reid et al. 1995). For GL 710 Mülläri & Orlov predict a future close approach distance of $259 \times 10^3 \text{ AU}$ in about 1 Myr assuming linear motion, and $279 \times 10^3 \text{ AU}$ in about 1 Myr using the model of galactic potential, compared to our values of $71 \times 10^3 \text{ AU}$ and 1.36 Myr. The difference between their results and ours for GL 710 is mainly due to the much

larger proper motion value reported for this star in the Catalogue of Nearby Stars than the one reported in the Hipparcos Catalogue.

3.2. The future close passage of GL 710

GL 710 is a late-type dwarf star (dM1 according to Joy & Abt 1974; K7 V according to Uppgren et al. 1972), currently located at a distance of 19.3 pc from the Sun, with an estimated mass of 0.4 to 0.6 M_{\odot} and a visual magnitude of 9.66. Based on its very small proper motion and using a radial velocity of -23 km s^{-1} , Vyssotsky (1946, see also Gliese 1981 and Gliese et al. 1986) predicted that GL 710 will have a close passage with a minimum distance of less than 1 pc in about a half million years. However, in the Preliminary Version of the Third Catalogue of Nearby Stars, Gliese & Jahreiss (1991) list a considerably smaller radial velocity for GL 710, -13.3 km s^{-1} , based on the value reported by Stauffer & Hartmann (1986, Jahreiss 1997). Because this change in the radial velocity has such a large impact on the time and distance calculated for the closest approach, we have looked carefully at the published data and have made new velocity measurements of our own.

There is some evidence that GL 710 may be a binary, but that evidence is far from conclusive. On the astrometric side, residuals in the proper-motion measurements suggested a possible periodicity of 1700 days (Osvalds 1957). A slight indication of a period of this order was also found by Grossenbacher et al. (1968), although they did not consider it to be of great significance. However, a speckle measurement of this star did not detect any companion with $\Delta m \leq 3$ and angular separation in the range $0.05''$ - $1''$ (Blazit et al. 1987). Furthermore, the Hipparcos astrometric data do not show any evidence of a non-linear proper motion during an observation period of 3.4 years (Kovalevsky 1996).

On the spectroscopic side there is some evidence that the radial velocity may have

changed by about 10 km s^{-1} over the past 50 years. We list in Table 3 the radial velocities reported in the literature plus five new values measured with the CfA Digital Speedometers. The first four values in Table 3 (Abt 1973) are from observations at the Mt. Wilson Observatory, and their weighted mean (-23.3 km s^{-1} , quality b) is reported in the General Catalogue of Stellar Radial Velocities (Wilson 1953).

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Based on the values listed in Table 3, GL 710 appears to exhibit a long-term radial velocity drift of about 10 km s^{-1} over 50 years. The measurements made in the 1940's show radial velocities more negative than -20 km s^{-1} , whereas the observations between 1984 and 1998 report values less negative than -15 km s^{-1} (with the sole exception of the value of $-26.3 \pm 15.0 \text{ km s}^{-1}$, which can be discounted due to its large uncertainty). However, we believe that this radial-velocity difference may not be real, and may instead be due to a systematic error in the zero point of the four Mt. Wilson observations made in the 1940s. As far as we can tell, all of the older velocities are derived from the same four Mt. Wilson spectra (Abt 1973, Joy & Mitchell 1948, Vyssotsky 1946). To assess the zero point of the old Mt. Wilson velocities we have compared the radial velocities of 27 single stars (including GL 710) observed at Mt. Wilson and listed by Joy & Mitchell (1948) with measurements of the same stars made at CfA. We find a mean difference (CfA minus Mt. Wilson) of about 9 km s^{-1} and an r.m.s. of 7.4 km s^{-1} .

Furthermore, there is no evidence for any drift in the recent CfA velocities. Although these observations span only 520 days, the allowed velocity drift is only a few tenths of a km s^{-1} at most.

In addition, it can be argued that it would be unlikely for an unseen main-sequence companion to produce the suggested drift of about 10 km s^{-1} over 50 years. Such a

companion could not be more massive than about 0.3 or $0.4 M_{\odot}$, otherwise its spectrum would have been seen and the companion would have been detected by the speckle observations. But, a circular orbit for such a companion with a period of 100 years would produce a velocity amplitude of at most about $\pm 6 \text{ km s}^{-1}$. One way to get a larger velocity amplitude would be to invoke an unseen evolved remnant for the companion, such as a massive (but cool) white dwarf. But, then the astrometric motion of GL 710 would have to be large, on the order of 1 arc second amplitude for the full orbit. For an orbital period of 100 years, the motion during the Hipparcos mission would hardly have departed from a straight line segment, but it would have been absorbed in the proper motion measurement. This would require that the orbital motion of GL 710 just happened to cancel out the space motion of the system at the time of the Hipparcos mission. However, the proper motion was also measured to be very small by Vyssotsky (1946), and therefore the orbital and space motion would also have cancelled 50 years ago. This is not consistent with supposing that the system was in a significantly different phase of its orbit, as would be required to explain the radial-velocity difference.

Another way to increase the velocity amplitude would be to invoke a shorter period, but this would also be hard to reconcile with the observations.

Therefore, we have chosen to assume that GL 710 is not a binary, and we have adopted the mean of the recent CfA values, -13.9 ± 0.2 , for its radial velocity. However, we must caution that the possible binary nature of GL 710 has not been fully ruled out, and additional monitoring of the radial velocity and/or astrometric positions over the coming years or even decades is clearly desirable for settling this issue.

Adopting a mean radial velocity of -13.9 km s^{-1} from the 5 recent CfA measurements, we obtain a miss distance and an encounter time of 0.342 pc and 1.36 Myr, respectively. We have also integrated the galactic orbits of GL 710 and the Sun. The integrated orbits predict

a closest approach distance and encounter time of 0.336 pc and 1.36 Myr, respectively, in excellent agreement with those we found with our linear motion approximation.

The Hipparcos proper motion measurement for GL 710 could be improved by VLBI astrometric observations if the star were a sufficiently strong radio emitter (at least 1 mJy). Since GL 710 has been designated as a late-type dwarf star it might be a detectable radio source. We observed GL 710 at 8.4 GHz with the VLA³ on 21 January 1997 to determine its flux density as a precursor to possible VLBI observations. No radio emission was detected from GL 710 with a conservative upper limit of 0.2 mJy.

4. DYNAMICAL EFFECT ON THE OORT CLOUD

The dynamical effect of stellar passages on the Oort cloud depends not only on their proximity but also on the mass of the star and how long each encounter lasts. The relative influence of these stars on the cometary orbits can be estimated from the differential attraction exerted on the Sun and a comet in the cloud, which results in a net change of the velocity of the comet relative to the Sun. The velocity perturbation, ΔV , on an Oort cloud comet or on the Sun due to a single stellar passage is approximately equal to $2GM_*V_*^{-1}D^{-1}$, where G is the gravitational constant, M_* is the mass of the star, V_* its total velocity relative to the Sun and D the miss distance (Oort 1950). The velocity impulse is directed at the star's point of closest approach. The relative magnitude of the differential velocity perturbation between the comet and the Sun can be estimated by multiplying ΔV by a term r/D , where r is the distance between the comet and the Sun.

In addition, the cumulative effect of close passages of several stars not necessarily

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belonging to the same multiple system but closely spaced in time may also play a role. Stochastic encounters with stars sufficiently massive and closely spaced in time should result in a somewhat larger effect than considering them separately. However, to be significant, such encounters would need to be spaced at intervals less than or equal to the time for a typical star to transit the Oort cloud. For instance, if we take a star’s path length of 10^5 AU through the outer Oort cloud (miss distance of about 86,000 AU), and a typical stellar encounter velocity of 40 km s^{-1} , then the star passages would need to be spaced within $\sim 12,000$ years to have a cumulative effect. Several temporal groups of encounters are present in our data. However, the uncertainties in the close approach times are typically larger than the Oort cloud transit time estimated above, and thus we can not reliably say that any of these groups are real. In addition, since the effects of these random encounters will add stochastically, we see no evidence for temporal groups whose cumulative effect would be more significant than the individual closest single star passages which we have predicted.

The relative magnitudes of the strongest predicted stellar perturbations on the Oort cloud, as derived from the above considerations, are listed in Table 4 and shown in Figure 6 for the seven major perturbers. The magnitudes are given in arbitrary units and represent a first-order measure of the gravitational influence of one close stellar passage relative to the others. This identifies the stars most likely to perturb the Oort cloud. However, the actual perturbation on the cometary orbits can only be estimated through dynamical simulations.

EDITOR: PLACE TABLE ?? HERE.

The most significant perturbers in our data set are SAO 128711 (HIP 1692) and GL 710 (HIP 89825). A mass of $0.7 M_{\odot}$ has been used for SAO 128711, and $0.5 M_{\odot}$ for GL 710. The close encounter of Algol (HIP 14576), a triple star system whose relative perturbation

has been calculated considering the total mass of the system ($5.8 M_{\odot}$, Martin & Mignard 1998), was already determined by VLBI astrometry by Lestrade et al. (1997) to be 7.3 Myr ago at 3 pc, in good agreement within the uncertainties with our values of 6.9 Myr and 2.7 pc. Algol’s large total mass and low encounter velocity compensate for the comparatively larger miss distance.

EDITOR: PLACE FIGURE 6 HERE.

We conducted dynamical simulations of stars passing close to the Oort cloud, in order to further evaluate the possible perturbative effects of our predicted closest stellar encounters. We used the dynamical model of Weissman (1996b) which uses the impulse approximation to estimate the velocity impulses on the Sun and on hypothetical comets, and thus the changes in the orbits of comets in a modeled Oort cloud. The simulations confirmed the relative expected magnitude of the perturbations shown in Table 4.

Based on simulations containing 10^7 and 10^8 hypothetical comets, we find that the maximum effect occurs, as expected, for the encounters with SAO 128711 and GL 710. Each of these stars results in a minor shower with $\sim 4 \times 10^{-7}$ of the Oort cloud population being thrown into Earth-crossing orbits. Assuming an estimated Oort cloud population of 6×10^{12} comets (Weissman 1996a), this predicts a total excess flux of about 2.4×10^6 comets in each shower.

However, because the arrival times of the comets are spread over about 2×10^6 years, the net increase in the Earth-crossing cometary flux is only about 1 new comet per year. This can be compared with the estimated steady-state flux of ~ 2 dynamically new (i.e., comets entering the planetary system directly from the Oort cloud) long-period comets per year (Weissman 1996a). Thus, the net increase in the cometary flux is about 50%. Since long-period comets likely account for only about 10% of the steady-state impactor flux

at the Earth (Weissman 1997), the net increase in the cratering rate is about 5%. This increase is likely not detectable given the stochastic nature of comet and asteroid impacts.

5. CONCLUSIONS

The study of the possible perturbation of the Oort cloud by passing stars has important implications for our understanding of the solar system. The identification of potential perturbers is thus necessary not only to estimate the recent past cometary flux caused by close stellar encounters and its possible correlation with the observed impact rate on Earth, but also to predict future passages and estimate their perturbative effect.

In this paper we have studied the close passages of stars using Hipparcos data. Radial velocity measurements from the literature plus others from our observations have been used to estimate the heliocentric velocities of these stars and to calculate these passages. From our data set we derive a rate of close stellar passages of 4.2 stellar systems per Myr passing within 1 pc, which we consider a lower limit since there is evidence for observational incompleteness in our sample.

We have identified several stars whose close passage could cause a significant perturbation of the Oort cloud. In order to investigate the effect of such passages on the cometary orbits, we have carried out dynamical simulations. This is the first time that such simulations have been performed for actual stellar passages. In general, the effect of these passages depends not only on the miss distance, but also on the total mass of the star system and on its relative velocity. Therefore, a suitable combination of mass and velocity could result in a larger perturbation for more distant passages than for closer ones.

For the future passage of GL 710 of less than 0.5 pc, the star with the most plausible closest approach in our sample, we predict that about 2.4×10^6 new comets will be thrown

into Earth-crossing orbits over a period of about 2×10^6 years. Many of these comets will return repeatedly to the planetary system, though about half will be ejected on the first passage. These comets represent an approximately 50% increase in the flux of long-period comets crossing the Earth's orbit.

From our estimated miss distances we conclude that no substantial enhancement of the steady-state cometary flux would result (or would have resulted) from the stars in our sample. However, further measurements of radial as well as transverse velocities are required to improve the accuracy of the estimates of the close approach distances for stars that are possible members of binary or multiple systems. Further measurements are also required for stars for which the possibility of a very close or even penetrating passage through the Oort cloud still remains open, because of the large errors in their predicted miss distances.

In order to complete our study, we are continuing to carry out an observational program to measure radial velocities for those stars in our initial sample of 1,208 stars with no previously published values. This will allow us to identify possible binary or multiple star systems. These measurements, together with analysis of the full data of the Hipparcos and Tycho Catalogues (ESA 1997), will likely increase the number of stars having close passages.

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Fig. 1.— Miss distance (10^3 AU) versus time (10^3 yr) of predicted stellar approaches within 5 pc. The outer radius of the Oort cloud is approximately 10^5 AU. The size of each point is proportional to the star’s visual brightness at closest approach (stars with bigger circles are brighter). These visual magnitudes range between -3.5 and 12.

Fig. 2.— Logarithmic plot of the cumulative number of predicted stellar encounters versus closest approach distance (10^3 AU) within ± 1 Myr. The dashed line is a least squares fit to the data. The slope of 2.02 ± 0.03 is in excellent agreement with theoretical expectations. The predicted encounter rate is $4.2 \text{ stars Myr}^{-1} \text{pc}^{-2}$, less than predicted values. This is likely due to observational incompleteness in the Hipparcos data set.

Fig. 3.— Closest predicted stellar passages within the past 2 Myr. Error bars in time and miss distance are plotted at the closest distance. SAO 128711 is plotted as a possible passage through the Oort cloud, but note the large uncertainty for this passage.

Fig. 4.— Same as Fig. 3 but up to 2 Myr in the future. GL 710 has the most plausible passage through the Oort cloud in our sample. Stars having predicted close passages within the next 0.1 Myr are identified in Fig. 5.

Fig. 5.— Same as Fig. 3 and 4 but for ± 100 kyr. Several close passages are predicted over the next few tens of thousand years.

Fig. 6.— Relative magnitude of the largest perturbers on the Oort cloud in our sample. The relative magnitude of the perturbation is proportional to $M_\star r / V_\star D^2$, where M_\star and V_\star are the mass and encounter velocity of the star, respectively, r is the radius of the Oort cloud, and D is the miss distance. Dot size indicates the relative magnitude of the perturbation.

TABLE 1. CfA radial velocities.

HIP ^a	T_{eff}^b	$v \sin i^c$	Nobs	Tspan ^d	V^e	error ^c	ext ^c	int ^c	e/i	χ^2	$P(\chi^2)$	Comments ^e
1463	3750	0	4	392	-15.15	0.36	0.42	0.72	0.59	0.79	0.851769	
1692	5000	0	3	375	18.14	0.31	0.54	0.47	1.15	2.97	0.226352	
2365	5250	0	5	269	-30.44	0.20	0.30	0.45	0.67	2.13	0.712650	
11048	3750	0	2	1131	-37.49	0.31	0.40	0.44	0.91	0.84	0.360620	U039
11559	7250	10	4	408	20.87	0.83	1.67	0.73	2.29	16.43	0.000925	S?
15929	6500	30	3	290	13.22	0.72	1.24	1.24	1.00	2.05	0.359264	
17085	6750	0	2	240	5.74	0.32	0.18	0.45	0.40	0.16	0.691640	
20359	4500	0	4	343	-78.51	0.18	0.31	0.36	0.86	2.78	0.426808	U077
20917	4500	0	60	4323	-35.19	0.06	0.44	0.41	1.06	67.10	0.219143	Gls169
21158	6250	0	5	1462	6.78	0.16	0.31	0.35	0.89	3.08	0.543902	H028676
21386	6500	10	7	1010	-50.72	1.37	3.63	0.68	5.33	204.55	0.000000	H026367,S
23452	3750	0	1	0	-17.13	0.43	0.00	0.43	0.00	0.00	1.000000	U092
23913	5500	0	4	383	-26.97	0.26	0.53	0.49	1.08	5.54	0.136311	
26335	3750	0	4	378	21.90	0.23	0.09	0.46	0.20	0.16	0.983637	U105
30067	6250	0	6	1552	40.19	0.14	0.24	0.35	0.68	2.39	0.792919	H043947
30920	3500	0	69	4364	17.93	0.15	1.27	1.08	1.18	106.92	0.001814	Gls234
31626	4500	0	2	76	82.68	0.24	0.08	0.34	0.23	0.05	0.814880	U117
33275	6500	10	3	320	-14.45	0.25	0.34	0.43	0.78	1.13	0.567759	
35136	6000	0	6	1758	84.20	0.20	0.32	0.50	0.65	2.51	0.774867	H055575
35389	8500	100	3	338	22.11	2.34	2.57	4.06	0.63	0.99	0.610781	
36208	3750	0	66	5258	18.23	0.12	0.60	0.97	0.61	23.59	0.999999	Gls273
38228	5750	10	6	1587	-15.93	0.22	0.19	0.54	0.35	1.01	0.961815	H063433
39986	8750	120	6	455	26.39	7.43	18.20	5.73	3.18	40.81	0.000000	S
40317	5750	0	3	329	34.18	0.24	0.28	0.42	0.67	1.03	0.596886	
41820	5500	0	8	1870	-16.12	0.18	0.51	0.34	1.52	17.38	0.015121	
43175	5500	0	4	384	19.90	0.19	0.21	0.37	0.56	1.06	0.786829	
49908	4500	0	134	4444	-25.92	0.04	0.44	0.33	1.33	226.52	0.000001	Gls380
52097	6500	30	7	340	-9.25	0.58	0.88	1.52	0.58	1.71	0.944082	
57548	3750	0	16	4033	-30.85	0.27	0.81	1.07	0.76	8.47	0.903657	U223
68061	6250	10	7	365	-33.59	0.33	0.87	0.86	1.01	5.78	0.448557	
75311 ^f	6000	0	4	355	-13.87	0.31	0.22	0.62	0.35	0.33	0.953365	
75311 ^g	6250	0	4	355	-14.80	0.27	0.26	0.53	0.49	0.80	0.849277	
79667	9250	70	3	329	-18.86	2.11	1.25	3.66	0.34	0.49	0.782547	
80459	3750	0	5	3802	-13.03	0.28	0.43	0.63	0.68	1.82	0.769203	U342
80824	3750	0	19	1006	-21.04	0.23	0.93	1.00	0.93	12.90	0.797476	U347
81935	4750	0	2	85	-19.07	0.18	0.25	0.25	1.03	1.07	0.300651	
82003	4500	0	139	4446	-31.35	0.04	0.50	0.34	1.45	308.57	0.000000	Gls638
85605	5000	0	4	232	-21.11	0.24	0.49	0.42	1.15	4.15	0.245367	
85661	7500	90	6	385	-45.98	1.67	4.10	2.39	1.71	15.83	0.007344	
86961	4500	0	1	0	-28.87	0.88	0.00	0.88	0.00	0.00	1.000000	
86963	3750	20	1	0	-27.36	2.28	0.00	2.28	0.00	0.00	1.000000	
88574	3750	0	1	0	32.06	0.60	0.00	0.60	0.00	0.00	1.000000	U387
89825	4250	0	5	526	-13.90	0.19	0.16	0.41	0.39	0.59	0.963754	
90112	5250	0	2	58	25.95	0.28	0.13	0.39	0.32	0.10	0.746999	
91768	3750	0	62	4933	-0.93	0.10	0.51	0.76	0.67	26.88	0.999956	Gls725A
91772	3750	0	59	4933	1.22	0.11	0.57	0.83	0.68	29.32	0.999390	Gls725B
92403	3500	0	1	0	-11.48	0.82	0.00	0.82	0.00	0.00	1.000000	U401
94512	8750	60	4	186	-30.67	1.75	3.50	2.04	1.72	6.22	0.101272	
94761	3750	0	4	783	35.38	0.39	0.44	0.77	0.57	0.99	0.804676	U412
95326	5000	10	2	58	35.56	0.42	0.11	0.59	0.19	0.04	0.846828	
99483	4750	0	3	169	25.03	0.23	0.23	0.40	0.58	0.72	0.696622	
100111	5750	0	4	120	26.07	0.28	0.57	0.52	1.10	2.94	0.401470	
101573	4750	0	3	481	43.65	0.51	0.88	0.53	1.65	5.94	0.051326	
103039	3750	0	3	155	15.82	0.56	0.59	0.97	0.61	0.77	0.681886	
103659	6750	20	3	66	-15.79	0.58	0.46	1.01	0.45	0.41	0.814551	
110893	3750	0	31	2164	-33.77	0.16	0.78	0.87	0.90	17.66	0.963768	U483
113020	3750	0	87	3746	-1.81	0.11	0.82	1.00	0.82	58.10	0.990909	Gls876

TABLE 1. (continued)

HIP ^a	T_{eff}^b	$v \sin i^c$	Nobs	Tspan ^d	V^e	error ^c	ext ^c	int ^c	e/i	χ^2	$P(\chi^2)$	Comments ^e
117042	7000	20	4	253	-8.56	0.48	0.58	0.96	0.61	1.03	0.793318	
117473	3750	0	48	4431	-71.16	0.09	0.46	0.62	0.75	27.74	0.988624	Gls908
117748	7500	30	4	269	7.38	0.66	0.76	1.33	0.57	0.82	0.845559	

^aHipparcos Catalogue number.^bIn K.^cIn km s⁻¹.^dIn days.^eSee text for details.^fNW component.^gSE component.

TABLE 2. Stellar passages within 5 pc of the Sun.

HIP ^a	Name ^b	R.A. ^c	DEC. ^c	Dist. ^d	σ_D ^e	Time ^f	σ_T ^g	V_r ^h	Mag. ⁱ	References ^j
1692	SAO 128711	00 21 13.32	-08 16 52.2	56.9	1045.4	-1241.3	945.1	18.1	-0.4	CfA
89825	GL 710	18 19 50.84	-01 56 19.0	70.6	33.2	1357.3	41.8	-13.9	0.9	CfA
93449	R CrA	19 01 53.68	-36 57 08.1	143.5	208.9	284.8	162.3	-28.0	6.2	Mendoza et al. 1969
85661 ^k	HD 158576	17 30 20.00	-04 22 09.8	155.4	139.7	1845.8	150.4	-46.0	-3.6	CfA
70890 ^k	Proxima	14 29 47.75	-62 40 52.9	196.8	7.5	26.7	0.2	-21.7	10.3	Matthews & Gilmore 1993
71683 ^k	α Centauri A	14 39 40.90	-60 50 06.5	200.7	4.3	27.8	0.1	-22.7	-0.7	Wesselink 1953
71681 ^k	α Centauri B	14 39 39.39	-60 50 22.1	201.1	4.3	27.7	0.2	-22.7	0.6	Wesselink 1953
57544	AC+79 3888	11 47 39.17	+78 41 24.0	207.6	5.2	42.8	0.9	-119.0	7.2	Wilson 1953
94512	HD 179939	19 14 10.04	+07 45 50.7	211.4	235.5	3732.9	451.0	-30.7	-3.1	CfA
80300	GL 620.1B	16 23 33.78	-39 13 46.2	234.9	19.6	-241.8	11.8	51.4	5.8	Holberg et al. 1995
87937 ^k	Barnard's star	17 57 48.97	+04 40 05.8	235.8	1.2	9.7	0.1	-110.9	8.5	Marcy et al. 1987
39986	HD 67852	08 09 58.46	+01 01 13.8	253.4 ^l	608.8	-4384.4	1357.2	26.4	-2.2	CfA
99483	HIP 99483	20 11 24.07	+05 36 19.9	284.5	5218.2	-2894.9	1452.0	25.0	2.5	CfA
54035 ^k	Lalande 21185	11 03 20.61	+35 58 53.3	297.0	1.3	20.0	0.1	-84.7	6.3	Marcy et al. 1987
100111	HD 351880	20 18 30.60	+19 01 51.8	298.0	748.8	-944.8	775.3	26.1	5.3	CfA
26624	HD 37594	05 39 31.15	-03 33 53.0	329.7	53.1	-1804.1	117.7	22.4	-1.1	Nordström & Andersen 19
26335	GL 208	05 36 30.99	+11 19 40.8	329.8	12.0	-497.9	8.6	21.9	4.5	CfA
27288	GL 217.1	05 46 57.35	-14 49 19.0	336.0	44.8	-1046.0	130.1	20.0	-2.1	Wilson 1953
38965	AQ Pup	07 58 22.09	-29 07 48.4	352.1	641.2	-1856.5	848.6	59.5	-0.6	Kovács et al. 1990
25240 ^k	HD 35317	05 23 51.33	-00 51 59.8	357.9	109.5	-1077.9	77.7	52.6	-1.5	Beavers & Eitter 1986
2365	SAO 74043	00 30 11.70	+22 24 01.1	358.4 ^l	1074.8	6719.7	1532.4	-30.4	-1.3	CfA
86963 ^k	GJ 2130B	17 46 14.47	-32 06 06.0	367.5	54.5	202.6	18.6	-27.4	8.7	CfA
85605 ^k	CCDM 17296+2439B	17 29 36.19	+24 39 11.6	379.0	143.4	196.8	28.3	-21.1	9.2	CfA
47425	GL 358	09 39 46.78	-41 04 06.3	386.7	56.3	-62.8	8.6	142.0	7.2	Rodgers & Eggen 1974
92403	Ross 154	18 49 48.96	-23 50 08.8	387.9	17.0	151.8	2.2	-11.5	9.4	CfA
101573	HIP 101573	20 35 07.18	+07 43 07.1	391.4 ^l	1259.8	-4202.4	1805.7	43.6	0.6	CfA
57548	Ross 128	11 47 44.04	+00 48 27.1	394.2	5.5	71.1	0.3	-30.9	9.9	CfA
86961 ^k	GJ 2130A	17 46 12.66	-32 06 10.0	397.9	75.4	189.0	13.2	-28.9	8.0	CfA
110893 ^k	GL 860A	22 28 00.42	+57 41 49.3	402.1	8.8	88.6	0.6	-33.8	8.0	CfA
23641	HD 33487	05 04 53.49	-69 10 08.0	403.0	76.7	1041.5	139.1	-39.0	2.6	Fehrenbach & Duflot 1982
40317	HD 68814	08 13 57.11	-04 03 12.6	410.4	276.5	-2347.3	298.8	34.2	1.5	CfA
30067	HD 43947	06 19 40.18	+16 00 47.8	415.8	24.2	-666.3	16.5	40.2	0.9	CfA
35550 ^k	GL 271A	07 20 07.39	+21 58 56.4	418.5	241.2	1138.0	111.7	-15.3	-1.2	Abt et al. 1980
21386	HD 26367	04 35 24.09	+85 31 37.2	420.3	58.9	704.5	42.5	-50.7	0.3	CfA
20359	GL 168	04 21 35.92	+48 20 13.1	428.0	59.5	380.5	22.5	-78.5	3.8	CfA
68061	BD+06 2809	13 56 09.08	+05 22 48.4	432.6	921.8	2175.5	1013.2	-33.6	3.6	CfA
38228	HD 63433	07 49 55.07	+27 21 47.6	437.5	25.3	1326.4	31.4	-15.9	1.8	CfA
16537 ^k	GL 144	03 32 56.42	-09 27 29.9	440.4	16.3	-104.9	0.8	16.8	2.8	Beavers & Eitter 1986
86214	GL 682	17 37 04.24	-44 19 01.0	441.4	127.0	67.4	15.1	-60.0	9.1	Rodgers & Eggen 1974
35389	SAO 96750	07 18 32.86	+17 53 41.6	448.6	675.2	-831.9	454.6	22.1	5.0	CfA
26744	HD 37574	05 40 57.82	+32 53 45.6	460.6	254.3	6054.1	1546.9	-10.0	-0.5	Wilson 1953
13772 ^k	GL 120.1	02 57 14.69	-24 58 09.9	463.2	50.0	-430.0	24.2	50.6	2.3	Gliese & Jahreiss 1991
86990	GL 693	17 46 35.44	-57 18 56.7	464.7	11.0	42.0	0.4	-115.0	8.7	Gliese & Jahreiss 1991
95326 ^k	CCDM 19236-3911B	19 23 38.93	-39 11 21.0	466.2	774.3	-342.9	239.3	35.6	8.6	CfA
68634	HD 122676	14 02 56.90	+14 58 31.2	466.6	80.8	-305.4	50.9	83.0	1.8	Fehrenbach et al. 1997
77257	GL 598	15 46 26.75	+07 21 11.7	467.7	9.0	165.7	1.6	-66.8	0.8	Duquenois & Mayor 1991
13769 ^k	GL 120.1C	02 57 13.18	-24 58 30.1	468.1	34.7	-503.2	19.2	49.6	2.6	Gliese & Jahreiss 1991
8709	WD 0148+467	01 52 02.96	+47 00 05.6	471.5	55.6	-237.2	13.7	64.0	8.2	Gliese & Jahreiss 1991
32349 ^k	Sirius	06 45 09.25	-16 42 47.3	474.3	18.3	65.7	5.5	-9.4	-1.7	Andersen & Nordström 19
113421	HD 217107	22 58 15.54	-02 23 43.2	479.2	64.2	1408.5	173.6	-13.5	1.5	Beavers & Eitter 1986
93506 ^k	HD 176687	19 02 36.72	-29 52 48.4	481.2	89.6	-1205.2	142.2	22.0	-2.7	Wilson 1953
31626	HD 260564	06 37 05.29	+19 45 10.7	482.8	69.9	-405.2	28.4	82.7	4.3	CfA
5643	GL 54.1	01 12 29.90	-17 00 01.9	501.0	33.5	-74.4	1.1	28.0	11.2	Wilson 1953
54806	HD 97578	11 13 12.33	-48 13 30.2	504.5	627.2	-1326.7	590.8	23.5	4.6	Barbier-Brossat 1989
77910	HD 142500	15 54 40.27	+08 34 49.2	507.0	220.7	2873.9	361.9	-25.1	-1.1	Evans 1978
82977	HD 152912	16 57 22.64	-25 47 58.5	508.6	788.2	-2722.8	734.6	50.0	1.5	Wilson 1953
103039	LP 816-60	20 52 33.20	-16 58 29.3	512.1	25.3	-269.9	6.4	15.8	9.7	CfA
17085	HD 22785	03 39 38.32	-04 08 54.3	525.4 ^l	1769.3	-13516.5	2133.1	5.7	2.1	CfA
1463	GL 16	00 18 16.59	+10 12 10.3	541.0	48.8	1019.2	41.2	-15.2	6.9	CfA
103738 ^k	HD 19995	21 01 17.46	-32 15 28.0	547.3	229.3	-3802.2	230.7	17.6	-2.4	Wilson 1953

TABLE 2. (continued)

HIP ^a	Name ^b	R.A. ^c	DEC. ^c	Dist. ^d	σ_D ^e	Time ^f	σ_T ^g	V_r ^h	Mag. ⁱ	References ^j
85429	IRAS 17249+0416	17 27 25.94	+04 13 39.1	548.3	396.8	542.5	327.9	-90.0	6.0	Smak & Preston 1965
14576 ^k	Algol	03 08 10.13	+40 57 20.3	549.9	130.3	-6895.4	867.6	4.0	-3.1	Wilson 1953
11559	SAO 75395	02 28 54.92	+21 11 22.7	554.4 ^l	826.6	-5541.7	1069.0	20.9	1.0	CfA
97649 ^k	GL 768	19 50 46.68	+08 52 02.6	557.2	9.0	139.5	1.2	-26.1	-0.6	Evans 1978
33275	HD 50867	06 55 17.44	+05 54 37.7	563.4	193.2	3472.8	182.9	-14.4	1.2	CfA
57791	HD 102928	11 51 02.23	-05 20 00.0	566.0 ^l	241.1	-5789.0	493.1	13.4	-1.7	Ginestet et al. 1985
72511 ^k	CD-25 10553	14 49 33.51	-26 06 21.7	568.9	86.0	-72.9	1.7	33.0	10.8	Rodgers & Eggen 1974
116727	GL 903	23 39 20.98	+77 37 55.1	575.8	12.2	300.1	4.9	-43.1	-0.3	Beavers & Eitter 1986
52097 ^k	HD 92184	10 38 43.16	+05 44 02.4	578.1 ^l	862.6	7349.4	961.8	-9.2	0.2	CfA
6379	GL 56.5	01 21 59.20	+76 42 37.3	582.3	32.5	704.0	35.7	-22.7	3.3	Wilson 1953
91726 ^k	HD 172748	18 42 16.42	-09 03 09.2	582.3	77.2	1248.5	66.0	-44.8	-1.8	Evans 1978
25001	HD 34790	05 21 12.69	+29 34 11.6	590.3	401.9	4456.5	350.0	-18.7	-1.7	Wilson 1953
117473	GL 908	23 49 11.95	+02 24 12.9	595.2	9.5	62.9	0.3	-71.2	7.4	CfA
116250	HD 221420	23 33 19.55	-77 23 07.2	595.2	26.2	-1184.4	18.2	26.0	0.6	Barbier-Brossat 1989
80543	HD 148317	16 26 39.21	+15 58 21.5	598.8 ^l	132.0	2108.0	198.0	-37.0	-0.5	Wilson 1953
30920 ^k	Ross 614	06 29 23.00	-02 48 44.9	602.4	10.3	-110.9	0.2	17.9	10.4	CfA
21158	HD 28676	04 32 07.91	+21 37 56.5	611.8	254.9	-5612.1	241.0	6.8	1.5	CfA
35136	GJ 1095	07 15 50.11	+47 14 25.5	612.3	14.1	-189.7	2.1	84.2	1.8	CfA
37766	Ross 882	07 44 40.38	+03 33 12.8	629.4	17.3	-160.3	1.4	26.6	9.7	Marcy et al. 1987
72509 ^k	GL 563.2B	14 49 32.69	-26 06 40.2	633.3	303.7	-71.6	4.0	33.0	11.2	Rodgers & Eggen 1974
75311 ^k	BD-02 3986	15 23 11.60	-02 46 00.5	639.9	1761.9	3987.4	1637.9	-14.3	4.3	CfA
103659	HD 199881	21 00 08.69	-10 37 41.7	640.7 ^l	337.3	4974.5	446.7	-15.8	0.4	CfA
81935	HD 150689	16 44 15.03	-38 56 36.6	648.8	19.3	701.6	10.9	-19.1	4.2	CfA
20917	GL 169	04 29 00.17	+21 55 20.2	657.7	15.9	294.1	3.0	-35.2	5.5	CfA
36795	GL 279	07 34 03.21	-22 17 46.3	659.3	22.1	-411.7	7.1	60.1	-0.1	Feast 1970
80824	GL 628	16 30 18.11	-12 39 35.0	661.7	8.0	86.0	0.2	-21.0	9.5	CfA
86162 ^k	GL 687	17 36 26.41	+68 20 32.0	662.8	77.9	78.8	0.2	-27.9	8.4	Wilson 1967
29271	GL 231	06 10 14.20	-74 45 09.1	670.2	10.4	-255.2	3.1	34.9	2.6	Evans 1978
8102 ^k	GL 71	01 44 05.13	-15 56 22.4	674.6	3.4	42.6	0.5	-16.4	3.3	Beavers et al. 1979
27075	HD 38382	05 44 28.41	-20 07 36.0	675.1	54.8	-634.8	45.9	38.7	1.9	Beavers & Eitter 1986
1242	GL 1005	00 15 27.67	-16 07 56.3	678.4	96.0	105.8	2.6	-29.0	10.5	Gliese & Jahreiss 1991
3829	Van Maanen's star	00 49 09.18	+05 23 42.7	686.3	23.1	-34.3	0.1	54.0	11.8	Greenstein & Trimble 1967
23913	HD 233081	05 08 16.22	+52 22 03.3	692.0	154.6	1841.8	131.4	-27.0	3.2	CfA
91438	GL 722	18 38 53.45	-21 03 05.4	698.0	44.8	-306.6	17.4	38.6	2.9	Beavers & Eitter 1986
37279 ^k	GL 280A	07 39 18.54	+05 13 39.0	709.1	6.5	29.6	7.1	-3.9	0.4	Andersen & Nordström 1983
1475 ^k	GL 15A	00 18 20.54	+44 01 19.0	715.4	2.9	-16.1	0.2	11.9	8.0	Marcy et al. 1987
88847	HD 166180	18 08 12.37	+30 59 56.0	719.2 ^l	1008.5	7281.9	1165.4	-29.7	-1.6	Wilson 1953
85667 ^k	GL 678	17 30 23.87	-01 03 45.0	722.5	33.0	201.0	4.4	-76.4	2.0	Batten & Fletcher 1971
91772 ^k	GL 725B	18 42 48.51	+59 37 20.5	725.1	12.8	-0.4	0.2	0.1	9.7	CfA
39757 ^k	HD 67523	08 07 32.70	-24 18 16.0	735.1	19.8	-394.0	6.1	46.1	-0.8	Duffot et al. 1995
91768 ^k	GL 725A	18 42 48.22	+59 37 33.7	735.9	6.7	-0.4	0.2	0.1	8.9	CfA
7751 ^k	GL 66	01 39 47.24	-56 11 47.2	736.4	20.2	-283.5	4.4	22.7	4.0	Wilson 1953
117748 ^k	BD+37 4901C	23 52 48.30	+38 41 10.8	747.0	1395.9	-4426.2	1616.8	7.4	5.2	CfA
43175	BD+53 1283	08 47 39.26	+53 21 17.2	754.4 ^l	1578.6	-9012.1	2514.0	19.9	1.2	CfA
90112	HD 168769	18 23 19.64	-39 31 12.0	755.4	225.9	-1886.3	159.6	25.9	3.6	CfA
36208	Luyten's star	07 27 24.16	+05 14 05.2	756.3	4.4	-13.9	0.1	18.2	9.8	CfA
105090	GL 825	21 17 17.71	-38 51 52.5	762.4	5.2	-19.6	0.6	24.2	6.5	Jones & Fisher 1984
99701	GL 784	20 13 52.75	-45 09 49.1	768.7	11.6	124.7	0.6	-31.1	6.9	Evans 1978
11048	GL 96	02 22 14.46	+47 52 47.7	774.7	22.8	279.9	4.0	-37.5	6.9	CfA
98698	GL 775	20 02 47.10	+03 19 33.2	774.7	44.9	372.5	20.1	-31.6	4.7	Bopp & Meredith 1986
89959	HD 168956	18 21 15.85	+26 42 24.3	775.9	223.9	2840.6	345.7	-25.3	1.9	Evans 1978
33226	GL 251	06 54 49.47	+33 16 08.9	786.8	13.0	-123.9	0.3	22.7	9.1	Marcy et al. 1987
49908 ^k	GL 380	10 11 23.36	+49 27 19.7	795.3	4.3	68.7	0.1	-25.9	6.1	CfA
33277	GL 252	06 55 18.69	+25 22 32.3	796.6	56.7	1028.6	61.0	-15.6	2.5	Barnes et al. 1986
68184	HD 122064	13 57 32.10	+61 29 32.4	797.8	33.4	333.3	11.3	-25.3	4.4	Wilson 1953
117042	HD 222788	23 43 34.71	+19 07 47.7	808.0	1238.5	2025.6	1094.9	-8.6	5.7	CfA
79667	HD 146214	16 15 33.26	-12 40 48.1	826.4	413.3	4845.5	719.2	-18.9	0.6	CfA
15929	HD 21216	03 25 10.64	-06 44 08.5	835.0 ^l	305.7	-5176.8	522.2	13.2	2.2	CfA
114059	HD 218200	23 05 56.62	+18 05 14.1	837.8	426.2	-4057.1	688.0	18.0	1.2	Fehrenbach et al. 1987
34603	GL 268	07 10 02.16	+38 31 54.4	838.7	29.5	-97.0	0.5	37.9	10.7	Tomkin & Pettersen 1986

TABLE 2. (continued)

HIP ^a	Name ^b	R.A. ^c	DEC. ^c	Dist. ^d	σ_D ^e	Time ^f	σ_T ^g	V_r ^h	Mag. ⁱ	References ^j
99859	HD 192869	20 15 36.34	+42 21 43.4	839.9	348.3	3905.4	471.4	-28.0	0.6	Wilson 1953
24502 ^k	HD 33959C	05 15 23.61	+32 41 05.1	845.0	1329.2	1827.0	961.3	-13.1	4.0	Abt 1970
101027 ^k	GL 791.1A	20 28 51.62	-17 48 49.2	846.4	85.7	-1578.8	106.6	18.4	0.4	Wilson 1953
45333 ^k	GL 337.1	09 14 20.55	+61 25 24.2	849.9	37.3	1287.2	44.6	-14.2	1.8	Soderblom & Mayor 1993
85523	GL 674	17 28 39.46	-46 53 35.0	852.8	64.2	73.7	21.5	-10.2	9.2	Catchpole et al. 1982
80337	GL 620.1A	16 24 01.24	-39 11 34.8	857.5	22.7	-867.1	9.0	13.0	2.9	Soderblom & Mayor 1993
11964	GL 103	02 34 22.52	-43 47 44.3	862.3	18.1	-233.2	2.7	41.9	6.7	Evans 1959
109555	GL 851	22 11 29.89	+18 25 32.7	866.8	30.5	188.2	2.7	-51.4	8.1	Marcy et al. 1987
90595	HD 170296	18 29 11.85	-14 33 56.9	882.7	282.5	2126.4	216.6	-41.0	-1.9	Wilson 1953
36186 ^k	HD 58954	07 27 07.99	-17 51 53.5	895.7	205.6	2872.0	262.2	-29.2	-0.9	Wilson 1953
27913 ^k	GL 222	05 54 23.08	+20 16 35.1	903.5	16.4	471.6	2.6	-13.4	2.9	Duquennoy & Mayor 1991
33909	HD 53253	07 02 15.48	-43 24 13.9	903.7	238.5	-3930.2	321.8	31.1	-0.8	Nordström & Andersen 1985
94761	GL 752A	19 16 55.60	+05 10 19.7	911.6	11.4	-70.4	0.1	35.4	8.5	CfA
86400	GL 688	17 39 17.02	+03 33 19.7	920.0	34.9	-381.4	9.4	22.7	4.6	Beavers & Eitter 1986
90790	GL 716	18 31 19.05	-18 54 30.0	924.8	24.9	274.7	4.3	-41.6	4.5	Catchpole et al. 1982
23452 ^k	HD 32450	05 02 28.51	-21 15 22.0	926.1	29.4	351.2	4.8	-17.1	6.9	CfA
41820 ^k	HD 71974	08 31 35.03	+34 57 58.3	941.5	100.2	1697.5	67.2	-16.1	3.3	CfA
7981 ^k	GL 68	01 42 29.95	+20 16 12.5	943.2	18.6	134.6	1.0	-33.9	4.2	Barnes et al. 1986
87345 ^k	HD 162102	17 50 52.34	-33 42 20.4	954.7	613.1	3595.6	603.4	-17.5	2.3	Wilson 1953
113020	Ross 780	22 53 16.16	-14 15 43.4	967.5	9.6	12.1	0.7	-1.8	10.2	CfA
88601 ^k	GL 702	18 05 27.21	+02 30 08.8	969.1	23.3	75.2	8.2	-9.7	3.9	Beavers & Eitter 1986
22449 ^k	GL 178	04 49 50.14	+06 57 40.5	969.7	41.1	-211.3	4.1	24.4	2.0	Beavers & Eitter 1986
88574	GL 701	18 05 07.25	-03 01 49.8	973.5	21.3	-150.6	0.9	32.1	8.3	CfA
16536	GL 145	03 32 56.11	-44 42 08.2	976.1	39.7	239.1	3.3	-36.0	9.7	Gliese & Jahreiss 1991
42049	HD 72617	08 34 13.35	+08 27 08.5	979.4	168.8	-1064.2	150.8	53.0	0.6	Fehrenbach et al. 1997
106440	GL 832	21 33 34.02	-49 00 25.3	995.9	6.8	-51.5	0.3	4.1	8.6	Barbier-Brossat 1989
82003	GL 638	16 45 06.38	+33 30 29.9	997.1	15.2	230.1	1.0	-31.4	6.6	CfA
89937 ^k	GL 713	18 21 02.34	+72 44 01.3	997.8	6.7	-155.5	0.2	32.4	2.4	Tomkin et al. 1987
110294	HD 239927	22 20 25.74	+58 05 05.3	1008.7	197.6	1570.6	114.2	-35.5	4.3	Barbier-Brossat 1989
80459	GL 625	16 25 24.19	+54 18 16.3	1009.8	14.5	220.7	0.9	-13.0	9.5	CfA
39780	HD 67228	08 07 45.84	+21 34 55.1	1015.9	51.0	598.8	17.2	-36.4	1.9	Abt & Levy 1976
92871	GL 735	18 55 27.36	+08 24 09.6	1016.2	45.8	687.9	9.7	-13.5	8.2	Gliese & Jahreiss 1991
53985	GL 410	11 02 38.25	+21 58 02.2	1027.1	49.0	529.7	16.3	-17.6	7.7	Young et al. 1987
82817 ^k	GL 644	16 55 29.24	-08 20 03.1	1027.7	32.7	-73.6	2.5	18.8	8.7	Evans 1978

^aHipparcos Catalogue number.^bGiven as alternative identification.^cRight Ascension and Declination for epoch J1991.25, as given in the Hipparcos Catalogue^dClosest approach distance (10^3 AU).^eDistance uncertainty (10^3 AU).^fTime of closest approach (10^3 yr). The sign indicates a past (negative sign) or future (positive sign) passage.^gTime uncertainty (10^3 yr).^hRadial velocity (km s^{-1}).ⁱVisual magnitude at closest approach.^jRadial velocity reference. CfA denotes measurements by the Center for Astrophysics. See text for details.^kStar listed in the Catalogue of Components of Double and Multiple Stars (Dommanget and Nys 1994).^lStar whose closest approach distance might need to be revised, according to differential acceleration Sun-star. See text for details.

TABLE 3. Radial velocity measurements for GL 710.

Date ^a	V_r ^b	References
7 Sep 1944	-21.5	Abt 1973
23 Sep 1944	-20.2	Abt 1973
29 Aug 1945	-23.0	Abt 1973
29 Sep 1945	-26.6	Abt 1973
Not reported	-22.8 ± 0.9	Vyssotsky 1946
Not reported	-23	Joy & Mitchell 1948
4 Mar 1984	-14.3	Stauffer & Hartmann 1986
8 Sep 1993	-26.3 ± 15.0	Reid et al. 1995
23 May 1994	-13.5 ± 2.0	Gizis 1997
5 Oct 1996	-13.89 ± 0.28	CfA
6 Oct 1996	-13.75 ± 0.30	CfA
8 Oct 1996	-13.73 ± 0.40	CfA
17 May 1997	-14.05 ± 0.37	CfA
15 Mar 1998	-14.08 ± 0.57	CfA

^aDate of observation.

^bRadial velocity (km s^{-1}).

TABLE 4. Potential perturbers of the Oort cloud.

Name	HIP	Time ^a	Distance ^b	Rel. magnitude ^c
SAO 128711	1692	-1253.0	57.4	100
GL 710	89825	1361.2	70.9	61
Algol	14576	-6895.4	549.9	41
AQ Pup	38965	-1856.5	352.1	21
Proxima + Alpha Cent	71681 ^e	27.7	201.1	14
HD 158576	85661	1962.3	165.2	13
HD 179939	94512	3715.9	210.5	12

^aTime of closest passage (10^3 yr).

^bMiss distance (10^3 AU).

^cRelative magnitude of the perturbation in arbitrary units. The values are proportional to $M_* r V_*^{-1} D^{-2}$ and are normalized to have value 100 for the largest perturbation.

^dAlthough no spectral type is reported for this star, a nominal value of 1 M_\odot is assumed. The relative magnitude can be considered as an upper limit.

^eThe HIP number given is for the Alpha Centauri B component, but the magnitude in the last column is for the triple system Proxima Centauri and Alpha Centauri A/B.

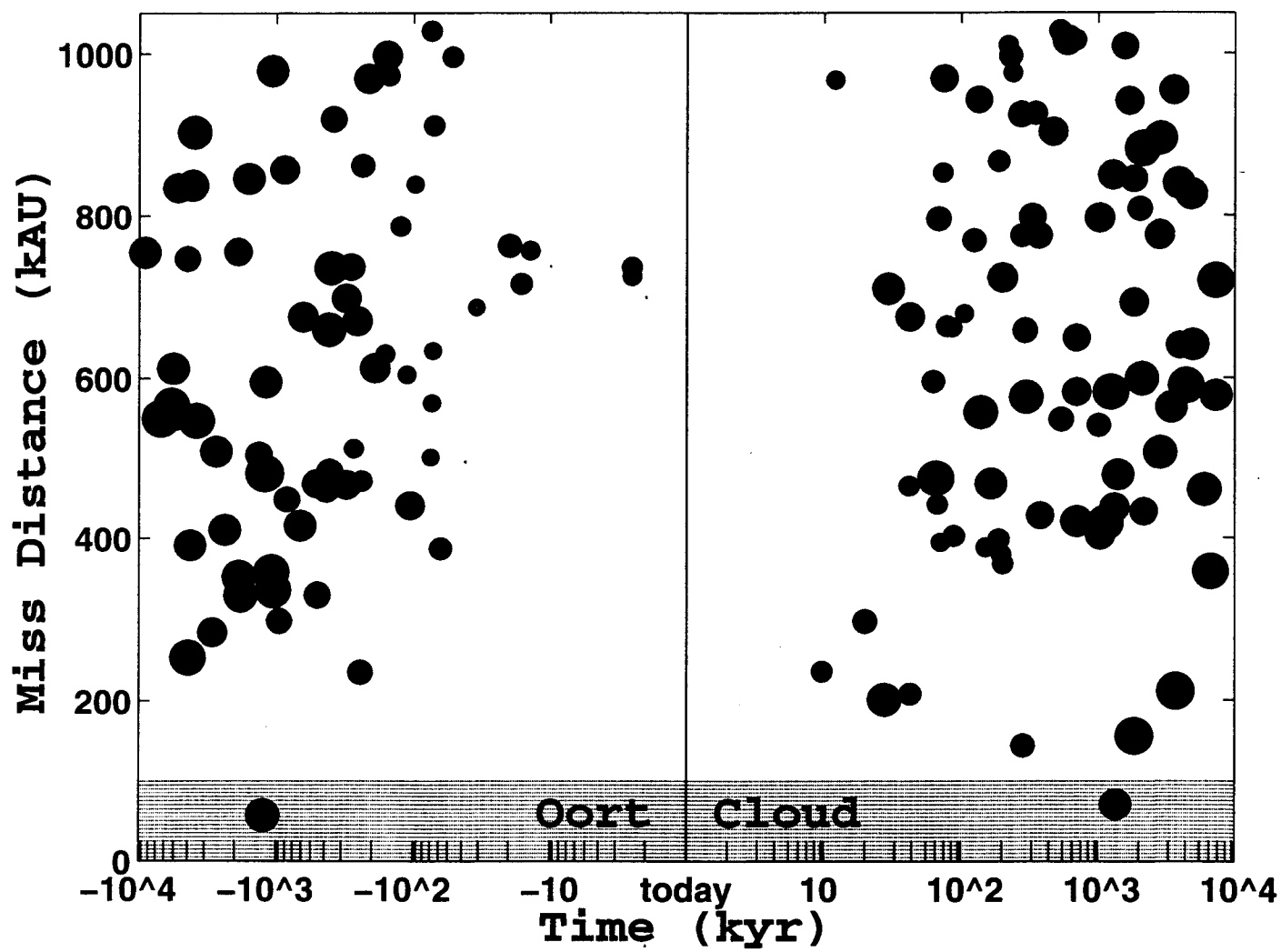
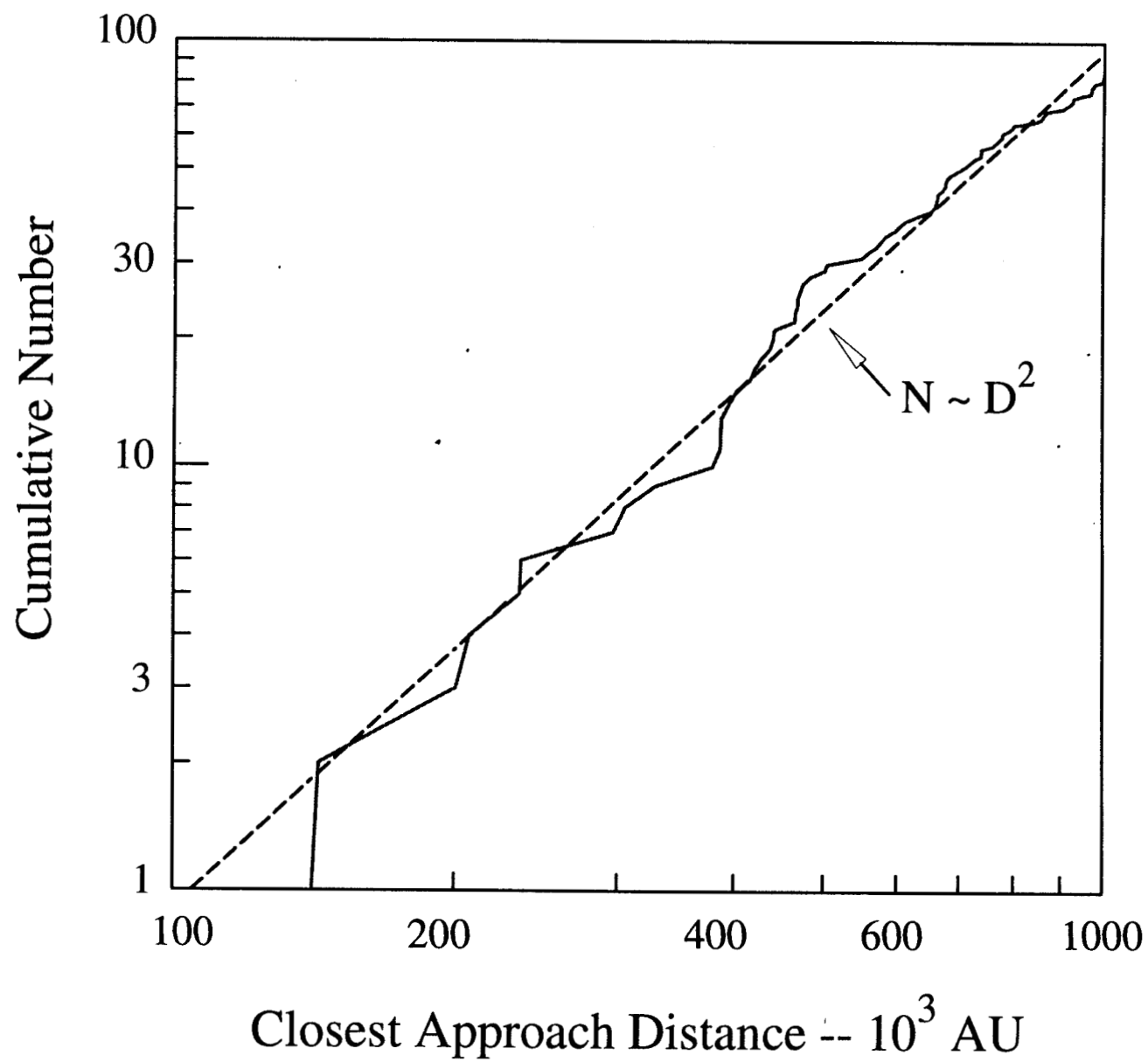


Fig. 1

Fig. 2



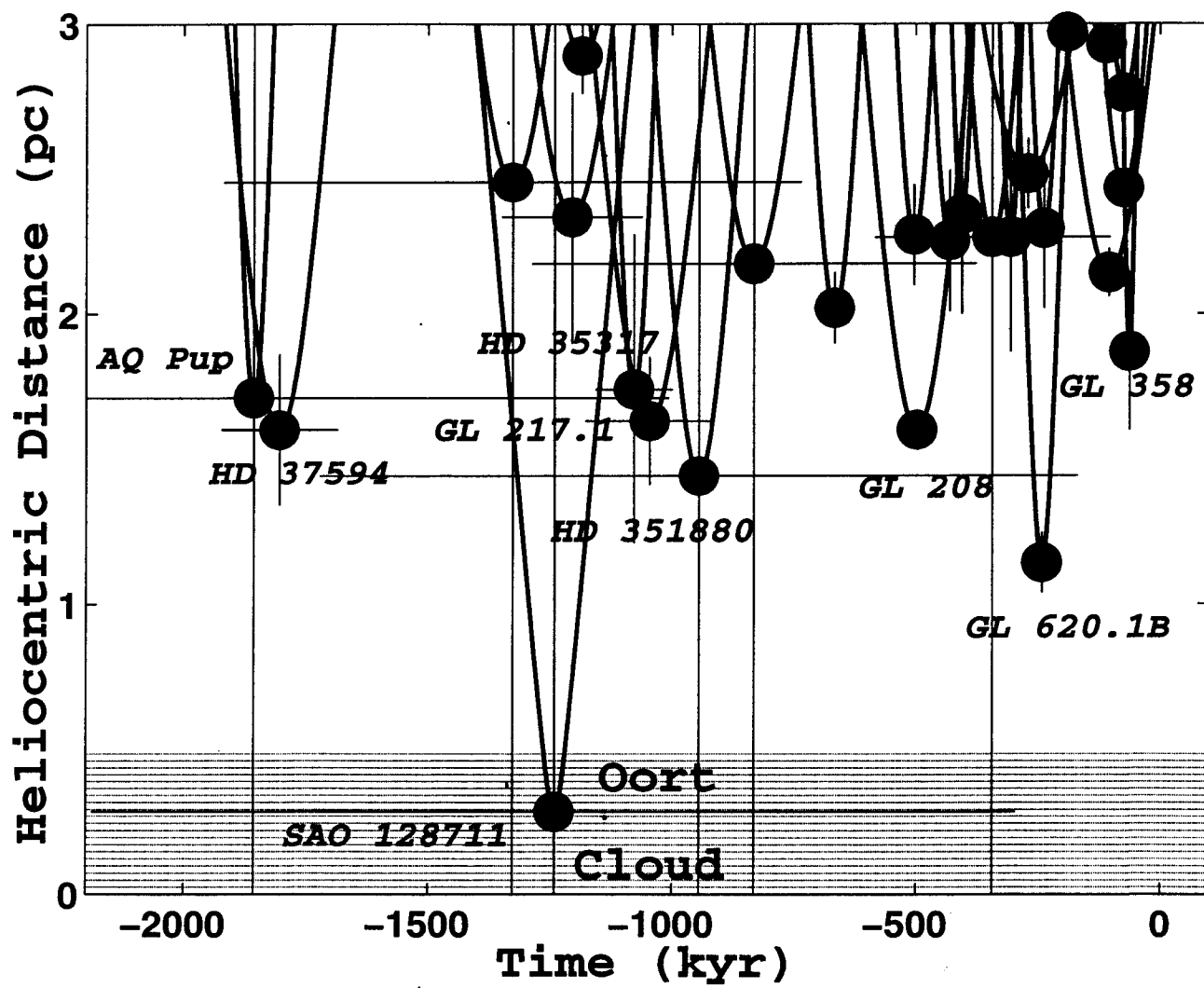


Fig. 3

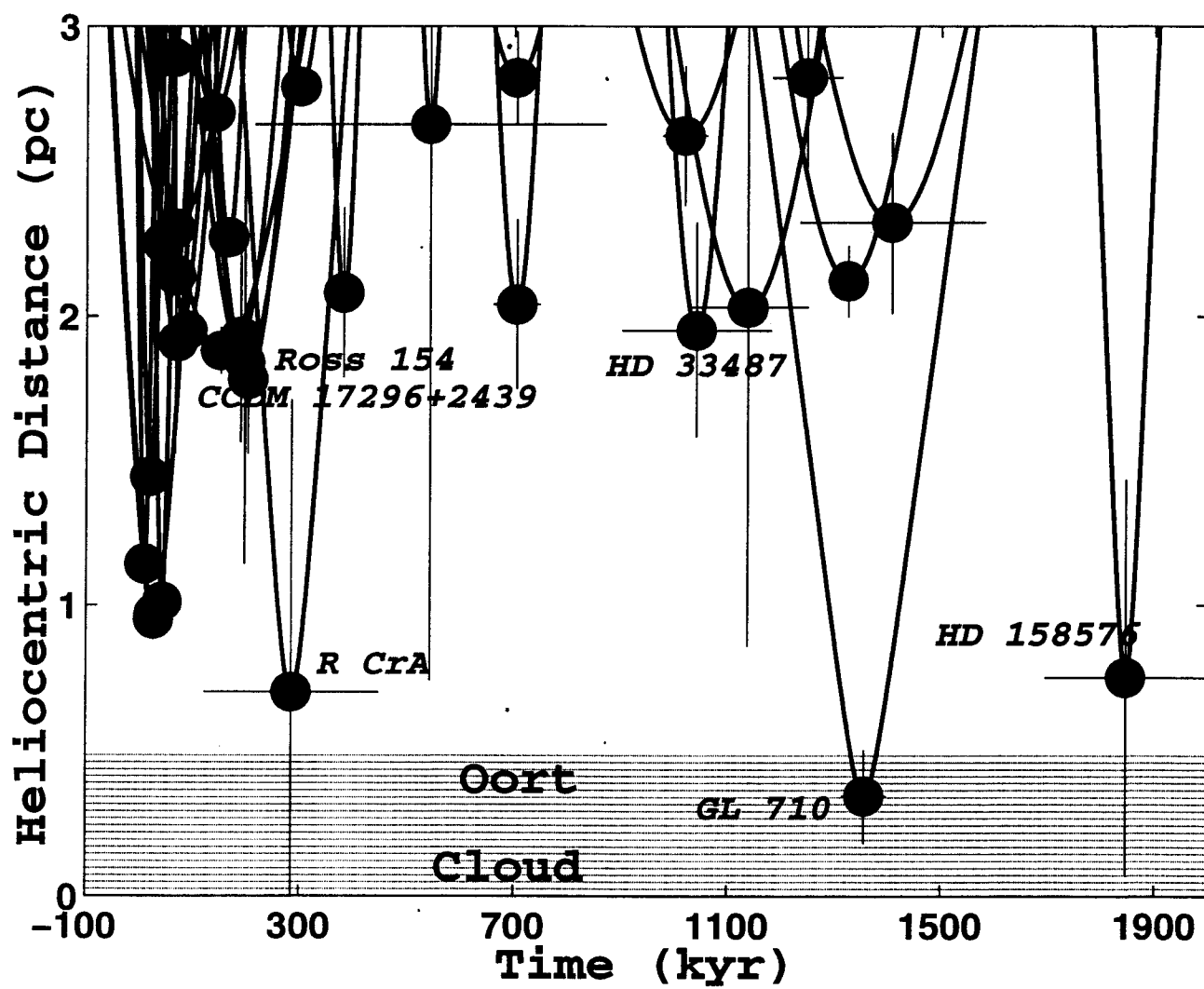


Fig. 4

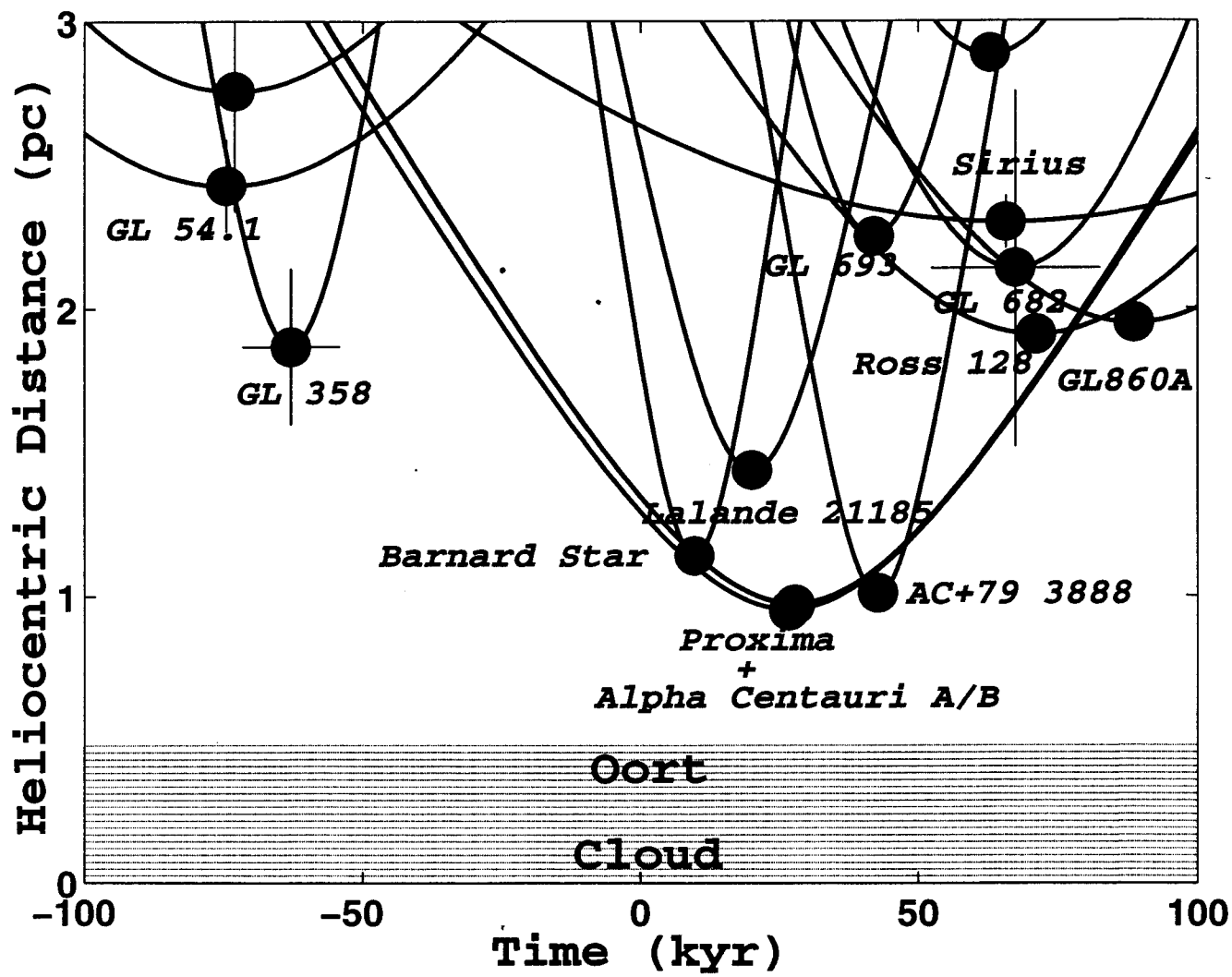


Fig. 5

Fig. 6

